(54) POWER FACTOR MEASUREMENT

(71) We, THE POST OFFICE, a British body corporate established by Statute of 23 Howland Street, London, W1P 6HQ, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to measuring the power factor of the dielectric material of a coaxial cable. In British Patent Specification No. 1,040,575 there is described a method of testing coaxial cable by measurement of the power factor of its dielectric material which includes the steps of initiating an electrical oscillation in a test resonant circuit including a test capacitor comprising a specimen of cable to be tested, supplying sufficient energy to the test resonant circuit to balance out losses other than those introduced by the test capacitor, and measuring the decrement of the oscillation in the test circuit to provide a measurement of the power factor of the dielectric material of the cable specimen.

In order to allow for the losses occurring in the test resonant circuit other than those introduced by the test capacitor, an indication the amount of electrical energy required to be supplied to the test resonant circuit to balance out the losses when used with a reference capacitor of the same capacitance as the test capacitor is obtained. The difference between the two amounts of electrical energy respectively required to balance out losses when the test capacitor and when the reference capacitor is connected to the test circuit then provides a measure of the energy necessary to balance out the losses in the test resonant circuit introduced by the test capacitor, but this measurement is, of course, subject to an offset due to the losses in the reference capacitor. In the parent specification the losses in the reference capacitor are assumed to be negligible, but although the losses are small they will give rise to some inaccuracy in the measurement.

It is an object of the present invention to provide an improved method of measuring the power factor of the dielectric material of a coaxial cable.

According to the present invention, there is provided a method of measurement of the power factor of the dielectric material of a specimen of coaxial cable treated as a test capacitor, including the steps of a) setting up an undamped electrical oscillation in a parallel resonant circuit including a reference capacitor, adjusted to have a capacitance equal to that of the test capacitor, by supplying a first amount of electrical energy to compensate for losses therein, b) substituting the test capacitor in the parallel resonant circuit for the reference capacitor, c) setting up and undamped electrical oscillation in the resonant circuit with the test capacitor by supplying a second amount of electrical energy to compensate for losses therein, d) and determining the difference between the first and second amounts of electrical energy to provide an indication of the power factor of the dielectric material of the cable specimen relative to that of the reference capacitor, wherein the power factor of the reference capacitor is desired using the method steps a), b), c) and d) with a calibration capacitor in the place of the test capacitor, the calibration capacitor being formed by a section of coaxial cable with air dielectric such that its power factor can be calculated from its dimensions and electrical parameters as determined by standard electrical measurements, whereby an absolute indication of the power factor of the dielectric of the cable specimen can be produced taking into account the power factor of the reference capacitor.

According to a second aspect of the invention, there is provided electrical test apparatus suitable for performing the method of measurement described above and according to any of claims 10 to 23 or 26 of British Patent Specification No. 1,040,575 including a calibration capacitor, connectible in parallel with the inductor as an alternative to the test capacitor, in the form of a length of

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coaxial transmission line having air dielectric such that the power factor of the calibration capacitor can be calculated from its dimensions and electrical parameters as determined by standard electrical measurements, whereby the power factor of the reference capacitor can be allowed for.

In order that the invention may be fully understood and readily carried into effect it will now be described with reference to the single Figure of the accompanying drawing which corresponds to Figure 3 of the aforementioned Specification, but shows the apparatus comprising a reference capacitor with a calibration capacitor.

The apparatus shown in the drawing consists of a change-over switch 1, having terminals 2 and 3 to which a contact blade 4 of gold leaf is alternately drawn by selectively applied suction. The contact blade 4 is connected to a terminal 5 which is equivalent to the terminal 16 in Figures 2 and 3 of the parent specification. The capacitors connected to the terminals 2 and 3 are joined alternately to the test resonant circuit represented by C1, L1 in the oscillator circuit of Figure 2 of the parent Specification. The terminals 2 and 3 are supported in respective insulating mountings 6 and 7 in an earthed casing 8. The reference capacitor CR is an adjustable coaxial capacitor having air dielectric with an outer electrode 9 secured to the casing 8 and an inner electrode secured to the terminal 2. The capacitor CR is provided with an adjustable cap 10 which screws on to the outer electrode 9 to adjust its capacitance. The calibration capacitor C_c consists of a length of coaxial cable with air dielectric having an inner conductor 11 and an outer conductor 12. The inner conductor 11 is joined to the terminal 3 and the outer conductor 12 is attached to a flange 13 which is secured to the casing 8. The capacitor C_c is provided with an end cap 14 for supporting the centre conductor at the end of the calibration capacitor and is shaped to minimise losses due to surface leakage. During testing a length of cable to be tested would be connected in place of the calibration capacitor C_c shown in the drawing.

The reference capacitor C_R has typically a nominal value of 32pF or 48pF, depending upon the capacitance of the cable sample whose power factor is to be tested. The method of testing follows one described in the parent Specification and is briefly as follows.

An oscillator circuit is set up including a parallel resonant circuit connected to an amplifier having positive feedback with a variable attenuator controlling the amount of positive feedback. In carrying out a test on a section of transmission cable, this is connected as a capacitor in the parallel resonant circuit, an oscillation is initiated by an impulse and the variable attenuator is adjusted so that the oscillator circuit just sustains the oscillation. The setting of the attenuator is noted. Prior to this a reference capacitor is connected in the parallel resonant circuit, the capacitance of the reference capacitor being adjusted to be equal to that of the section of cable being tested, and the variable attenuator adjusted so that the oscillator circuit just sustains an oscillation. This setting of the attenuator is noted, and the difference between the two settings is determined.

The power factor of the reference capacitor is determined by means of a similar test carried out using the reference capacitor and a calibration capacitor. The calibration capacitor consists of a length of air dielectric coaxial cable, the power factor of which can be calculated on the basis of its dimensions and its electrical parameters as determined by standard electrical measurements.

The adjustment provided by the cap 10 enables precise agreement to be obtained between the capacitance of the reference capacitor and that of the test sample. It is essential that the resonant frequencies with the reference and test capacitors connected in circuit are identical, otherwise variable losses in the amplifiers and cables will be introduced, which will interfere with the accuracy of the measurement. The cap 10 can also be used to follow changes of capacitance in the test sample due to changes in the test conditions, such as changes of temperature or air pressure.

The higher the capacitance of the test sample and the reference capacitor the greater the sensitivity of the apparatus, but this is offset by an increase in the conductor losses and propagation effects due to the greater length of cable involved. It is necessary to apply a correction for conductor resistance effects in the test sample and where these are large absolute accuracy suffers.

If a_1 and a_2 are the gain changes required to neutralise the damping effect of the power factors of the test capacitor and the power factor standard i.e. the calibration capacitor respectively in the resonant circuit when they are interchanged with the reference air capacitor, then, since the change of gain is proportional to the difference in power factor between the reference and test or reference and calibration capacitors,

$$\frac{a_1}{a_2} = \frac{\text{Tan } \Delta_1' - \text{Tan } \Delta_r'}{\text{Tan } \Delta_2' - \text{Tan } \Delta_r'}$$

where

Tan Δ_1' = effective power factor of test capacitor C_1 in resonator circuit

Tan Δ_2' = ditto for calibration capacitor C_2

Tan Δ_r' = ditto for reference capacitor C_r.

Due to the self capacitance of the inductor and residual capacitance the reference capaci-

tor is not completely replaced by one containing the test specimen. Since the change of gain is proportional to the inserted loss of the test capacitor, associated with the total capacitance across the inductor L_1, the residual shunt capacitance in the connections (etc) has the effect of reducing the measured power factor. This also applies to a calibration capacitor so, providing the test and calibration capacitors are the same, the effect is cancelled. When the test and calibration capacitors are not quite equal then a correction must be used.

The apparent loss angle Δ_1' of the test capacitor in parallel with the strays C_o is given by

$$\tan \Delta_1' = \frac{G_1}{\omega(C_1+C_o)}$$

$$= \frac{G_1}{\omega C_1} \cdot \frac{C_1}{C_1+C_o}$$

$$= \tan \Delta_1 \frac{C_1}{C_1+C_o}$$

where $\tan \Delta_1 =$ the tangent of the true loss angle Δ_1 of the test capacitor and G_1 is the conductance of the test capacitor. A similar correction should be applied to $\tan \Delta_2'$ and $\tan \Delta_r'$. $\tan \Delta_r'$ will have two values corresponding to the test and calibration measurements respectively, but providing the difference between C_1 and C_2 is less than 2pF. $\tan \Delta_r$ may be assumed to be constant. The error from this assumption is less than 0.05 micro radian, then:—

$$\frac{a_1}{a_2} = \frac{(\tan \Delta_1 - \tan \Delta_r)\dfrac{C_1}{C_1+C_o}}{(\tan \Delta_2 - \tan \Delta_r)\dfrac{C_2}{C_2+C_o}} \tag{1}$$

C_r being equal to C_1 and C_2 respectively in the two tests.

Finally it is necessary to apply a correction to the measured power factor of the test capacitor to correct for the loss due to the cable conductor resistance. This becomes quite significant above 1MHz for the size of test capacitor used in the specific design under consideration.

i.e.

$$\tan \Delta_1 = \tan \delta_1 + \tan \delta_o \tag{2}$$

where

$\tan \delta_1 =$ power factor of the dielectric
$\tan \delta_c =$ contribution due to its conductors.

Combining (1) and (2) we have

$$\tan \delta_1 = \frac{a_1}{a_2} \cdot \frac{C_2(C_1+C_o)}{C_1(C_2+C_o)} \tan \Delta_2$$

$$+ \tan \Delta_r(1-\frac{a_1}{a_2}) \frac{C_2(C_1+C_o)}{C_1(C_2+C_o)} - \tan \delta_o \tag{3}$$

If the calibration capacitor is designed to have approximately the same power factor and capacitance as the test capacitor, then a_1 will approach a_2 and:

$$\tan \delta_1 = \frac{a_1}{a_2} \cdot \frac{C_2(C_1+C_o)}{C_1(C_2+C_o)} \cdot \tan \Delta_2 - \tan \delta_o \tag{4}$$

Typical values for a measurement at 13MHz on a current submarine cable design where $C_x = 48$pF are:

$a_1 = 0.146$dB
$a_2 = 0.229$ dB
$\delta_1 = 74$ μ radians
$\delta_o = 29$ μ radians
$\Delta_2' = 163$ μ radians
$\Delta_r' = 3$ μ radians
C_o can be measured at low frequency by a capacitance bridge.

The power factor of the calibration capacitor may be determined from a consideration of an open circuit line acting as a capacitor.
The open circuit input admittance

$$Y_{oo} = Y_o \tanh \gamma . 1$$

where the characteristic impedance of the line

$$Z_o = \frac{1}{Y_o}$$

γ is the propagation constant and 1 is the length of the line.

$$\therefore Y_{oo} = Y_o . \frac{\sinh \gamma . 1}{\cosh \gamma . 1}$$

$$= Y_o \left[\frac{\gamma . 1 + \dfrac{(\gamma . 1)^3}{6} + \dfrac{(\gamma . 1)^5}{120} + \ldots}{1 + \dfrac{(\gamma . 1)^2}{2} + \dfrac{(\gamma . 1)^4}{24} + \ldots}\right]$$

$$= Y_o \left[\gamma . 1 - \frac{(\gamma . 1)^3}{3} + \frac{2(\gamma . 1)^5}{15} - \ldots\right]$$

now

$$Z_o = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$$

where R=the a.c. resistance of the conductor at the operating frequency
       L=the inductance of the conductors
       G=the conductance of the dielectric
       C=capacitance of the capacitor and

$$\gamma . l = \sqrt{(R+j\omega L)(G+j\omega C)}$$

$$\therefore Z_o^2(G+j\omega C) = \frac{(\gamma . l)^2}{(G+j\omega C)}$$

hence

$$\frac{1}{Z_o} = \frac{(G+j\omega C)}{\gamma . l} = Y_o$$

substituting for Y_o

$$Y_{oc} = \frac{(G+j\omega C)}{\gamma . l} \gamma . l - \frac{(\gamma . l)^3}{3} + \frac{2(\gamma . l)^5}{15} - \ldots$$

$$= (G+j\omega C) - (G+j\omega C) . \frac{(\gamma . l)^3}{3} + \frac{2}{15}(G+j\omega C)(\gamma . l)^4 - \ldots$$

$$= (G+j\omega C) - \frac{1}{3}(G+j\omega C)^2(R+j\omega L) + \frac{2}{15}(G+j\omega C)^3(R+j\omega L)^2 - \ldots$$

Higher order terms may be neglected, so

$$Yoc = (G+j\omega C) - \frac{1}{3}(G^2 - \omega^2 C^2 + j2\omega CG)(R+j\omega L)$$

$$= (G - \frac{1}{3}G^2 R + \frac{1}{3}\omega^2 C^2 R + \frac{2}{3}\omega^2 CGL) +$$

$$j(\omega C - \frac{2}{3}\omega CGR - \frac{1}{3}\omega LG^2 + \frac{1}{3}\omega^2 C^2 L)$$

If the admittance of an open circuit line acting as a capacitor is:

$$Yoc = G' + j\omega C'$$

Then $G' = G + \frac{1}{3}(-G^2 R + \omega^2 C^2 R + 2\omega^2 CGL)$

and $\omega C' = WC + \frac{1}{3}(-2\omega CGR - \omega LG^2 + \omega^3 C^2 L)$

and $\frac{G'}{\omega C'}$ = the effective power factor of the line,

where RLC and G are its primary constants.

In the case of the calibration capacitor it is an air line and G=0

Hence

$$\tan \Delta_2 = \frac{\dfrac{1}{3}\omega^2 C^2 R}{\omega C + \dfrac{1}{3}\omega^3 C^2 L.}$$

$$\fallingdotseq \frac{1}{3}\omega C R \text{ to an accuracy of}$$

0.2% up to 15 MHz.

This relationship can also be used to calculate $\tan \delta_0$, the contribution to loss angle in the test capacitor due to its conductors.

WHAT WE CLAIM IS:—

1. A method of measurement of the power factor of the dielectric material of a specimen of coaxial cable treated as a test capacitor, including the steps of

a) setting up an undamped electrical oscillation in a parallel resonant circuit including a reference capacitor, adjusted to have a capacitance equal to that of the test capacitor, by supplying a first amount of electrical energy to compensate for losses therein,

b) substituting the test capacitor in the parallel resonant circuit for the reference capacitor,

c) setting up an undamped electrical oscillation in the resonant circuit with the test capacitor by supplying a second amount of electrical energy to compensate for losses therein,

d) and determining the difference between the first and second amounts of electrical energy to provide an indication of the power factor of the dielectric material of the cable specimen relative to that of the reference capacitor,

wherein the power factor of the reference capacitor is derived using the method steps a, b, c, and d with a calibration capacitor

in the place of the test capacitor, the calibration capacitor being formed by a section of coaxial cable with air dielectric such that its power factor can be calculated from its dimensions and electrical parameters as determined by standard electrical measurements, whereby an absolute indication of the power factor of the dielectric of the cable specimen can be produced taking into account the power factor of the reference capacitor.

2. A method according to claim 1 in which the electrical energy is supplied to the resonant circuit by means of a variable gain amplifier connected to provide positive feedback to the resonant circuit, the gain of the amplifier required to sustain an initial amplitude of oscillations in the resonant circuit indicating the amount of electrical energy necessary to compensate for losses in the resonant circuit.

3. A method according to claim 1 or 2 in which oscillation in the resonant circuit is initiated by an electrical pulse.

4. Electrical test apparatus suitable for performing the method of measurement claimed in any preceding claim and according to any of claims 10 to 23 or 26 of British Patent Specification No. 1,040,575 including a calibration capacitor, connectible in parallel with the inductor as an alternative to the test capacitor, in the form of a length of coaxial transmission line having air dielectric such that the power factor of the calibration capacitor can be calculated from its dimensions and electrical parameters as determined by standard electrical measurements, whereby the power factor of the reference capacitor can be allowed for.

5. A method for testing coaxial cable according to any of claims 1 to 3 substantially as herein described with reference to the single Figure of the accompanying drawing.

ABEL & IMRAY,
Chartered Patent Agents,
Northumberland House,
303—306 High Holborn,
London, WC1V 7LH.